

Evidence for Planck-scale resonant particle production during inflation from the CMB power spectrum

Grant J. Mathews* and Mayukh R. Gangopadhyay

*Department of Physics, University of Notre Dame,
Notre Dame, IN 46556, USA*

**E-mail: gmathews@nd.edu*

Kiyotomo Ichiki

Department of Physics, Nagoya University, Nagoya 464-8602, Japan

Toshitaka Kajino

*National Astronomical Observatory of Japan
Mitaka, Tokyo 181-8599, Japan*

The power spectrum of the cosmic microwave background from both the *Planck* and *WMAP* data exhibits a slight dip for multipoles in the range of $l = 10 - 30$. We show that such a dip could be the result of the resonant creation of massive particles that couple to the inflaton field. For our best-fit models, the epoch of resonant particle creation reenters the horizon at a wave number of $k_* \sim 0.0011 \pm 0.0004$ ($h \text{ Mpc}^{-1}$). The amplitude and location of this feature corresponds to the creation of a number of degenerate fermion species of mass $\sim (8 - 11)/\lambda^{3/2} m_{pl}$ during inflation where $\lambda \sim (1.0 \pm 0.5)N^{-2/5}$ is the coupling constant between the inflaton field and the created fermion species, while N is the number of degenerate species. Although the evidence is of marginal statistical significance, this could constitute new observational hints of unexplored physics beyond the Planck scale.

Keywords: Inflation; cosmic microwave background; string theory

1. Introduction

In this paper we summarize an analysis¹ of a peculiar feature visible in the observed power spectrum near multipoles $\ell = 10 - 30$. This is an interesting region in the CMB power spectrum because it corresponds to angular scales that are not yet in causal contact, so that the observed power spectrum is close to the true primordial power spectrum.

The *Planck*² observed power spectrum in this region is shown in Figure 1 from Ref. [1]. Although the error bars are large, there is a noticeable systematic deviation in the range $\ell = 10 - 30$ below the best fit based upon the standard Λ CDM cosmology with a power-law primordial power spectrum. There is also a well-known suppression of the quadrupole moment in the CMB. These same features are visible in the CMB power spectrum from the Wilkinson Microwave Anisotropy Probe (*WMAP*)³, and hence, are likely a true feature in the CMB power spectrum, although it should be noted that in the Planck Cosmological parameters paper,⁴ the deviation from a simple power law in the range $\ell = 10 - 30$ was deduced to be of weak statistical significance due to the large cosmic variance at low ℓ .

A number of mechanisms have been proposed (see summary in Ref. [1]) to deal

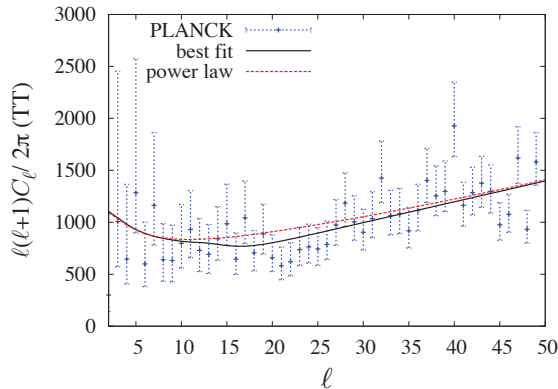


Fig. 1. (Color online) CMB power spectrum in the range of $\ell = 3 - 50$. Points with error bars are from the *Planck* Data Release². The dashed line shows the best standard Λ CDM fit to the *Planck* CMB power spectrum based upon a power-law primordial power spectrum. The solid line shows the best fit for a model with resonant particle creation during inflation.

with the suppression of the power spectrum on large scales and low multipoles. Most of these works, however, were concerned with the suppression of the lowest moments via changes in the inflation generating potential. In the present work¹, however, we are concerned specifically with suppression of the power spectrum in the range $\ell = 10 - 30$ due to the possibility that new trans-Planckian physics occurs near the end of the inflation epoch corresponding to the resonant creation^{5,6} of Planck-scale particles that couple to the inflaton field. Our best fit is shown by the solid line in Figure 1 which we describe in detail in the following sections.

This interpretation has the intriguing aspect that, if correct, an opportunity emerges to use the CMB to probe properties of new particle species that existed at and above the Planck scale ($m_{pl} \sim 10^{19}$ GeV). That is the goal of the present work. Indeed, string theory compactification schemes generically postulate the existence of massive particles at or above the Planck scale from the Kaluza-Klein states, winding modes, string excitations, etc. Moreover, the coupling of the inflaton to other particle species near the end of inflation is not only natural, but probably required. This is because the energy density in the inflaton must be converted to entropy in light or heavy particle species at the end of inflation as a means to reheat the universe. Hence, the existence of Planck-scale mass particles that couple to the inflaton near the end of inflation is a scenario that is both natural and even required. Moreover, this provides a possible opportunity to uncover new physics in the trans-Planckian regime.

2. Resonant Particle Production during Inflation

The details of the resonant particle creation paradigm during inflation have been explained in Refs. 1, 5, 6. Indeed, the idea was originally introduced⁷ as a means for

reheating after inflation. Since⁵ subsequent work^{8–11} has elaborated on the basic scheme into a model with coupling between two scalar fields.

In this minimal extension from the basic picture, the inflaton ϕ is postulated to couple to particles whose mass is of order the inflaton field value. These particles are then resonantly produced as the field obtains a critical value during inflation. If even a small fraction of the inflaton field is affected in this way, it can produce an observable feature in the primordial power spectrum. In particular, there can be either an excess in the power spectrum as noted in^{5,6}, or a dip in the power spectrum as described in this paper. Such a dip offers important new clues to the trans-Planckian physics of the early universe.

In the simplest slow roll approximation^{12,13}, the generation of density perturbations of amplitude, $\delta_H(k)$, when crossing the Hubble radius is just,

$$\delta_H(k) \approx \frac{H^2}{5\pi\dot{\phi}} , \quad (1)$$

where H is the expansion rate, and $\dot{\phi}$ is the rate of change of the inflaton field when the comoving wave number k crosses the Hubble radius during inflation.

For the application here,¹ we adopt a positive Yukawa coupling of strength λ between an inflaton field ϕ and a field ψ of N degenerate fermion species. The total Lagrangian density including the inflaton scalar field ϕ , the Dirac fermion field, and the Yukawa coupling term is simply,

$$\begin{aligned} \mathcal{L}_{\text{tot}} = & \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) \\ & + i \bar{\psi} \gamma^\mu \partial_\mu \psi - m \bar{\psi} \psi + N \lambda \phi \bar{\psi} \psi . \end{aligned} \quad (2)$$

For this Lagrangian, it is obvious that the fermions have an effective mass of

$$M(\phi) = m - N \lambda \phi . \quad (3)$$

This vanishes for a critical value of the inflaton field, $\phi_* = m/N\lambda$. Resonant fermion production will then occur⁵ in a narrow range of the inflaton field amplitude around $\phi = \phi_*$.

The cosmic scale factor is labeled a_* at the time t_* at which resonant particle production occurs. Considering a small interval around this epoch, one can treat $H = H_*$ as approximately constant (slow roll inflation). The number density n of particles can be taken as zero before t_* and afterwards as $n = n_* [a_*/a(t)]^3$. The fermion vacuum expectation value can then be written,

$$\langle \bar{\psi} \psi \rangle = n_* \Theta(t - t_*) \exp[-3H_*(t - t_*)] . \quad (4)$$

where Θ is a step function.

Then, one obtains¹ the perturbation in the primordial power spectrum as it exits the horizon:

$$\delta_H = \frac{[\delta_H(a)]_{N\lambda=0}}{1 + \Theta(a - a_*) (N \lambda n_* / |\dot{\phi}_*| H_*) (a_*/a)^3 \ln(a/a_*)} . \quad (5)$$

It is clear that the power in the fluctuation of the inflaton field will diminish as the particles are resonantly created when the universe grows to some critical scale factor a_* .

Using $k_*/k = a_*/a$, then the perturbation spectrum Eq. (5) can be reduced¹ to a simple two-parameter function.

$$\delta_H(k) = \frac{[\delta_H(a)]_{N\lambda=0}}{1 + \Theta(k - k_*)A(k_*/k)^3 \ln(k/k_*)} \quad (6)$$

where the amplitude A and characteristic wave number k_* ($k/k_* \geq 1$) can be fit to the observed power spectrum from the relation: $k_* = \ell_*/r_{lss}$, where r_{lss} is the comoving distance to the last scattering surface, taken here to be 14 Gpc. The values of A and k_* determined from the CMB power spectrum relate to the inflaton coupling λ and fermion mass m , for a given inflation model via Eqs. (5) and (6).

$$A = |\dot{\phi}_*|^{-1} N \lambda n_* H_*^{-1} \quad (7)$$

The connection between resonant particle creation and the CMB temperature fluctuations is straightforward. We have made a multi-dimensional Markov Chain Monte-Carlo analysis^{14,15} of the CMB using the *Planck* data² and the *CosmoMC* code¹⁵. For simplicity and speed in the present study we only marginalized over parameters which do not alter the matter or CMB transfer functions. Hence, we only varied A and k_* , along with the six parameters, $\Omega_b h^2, \Omega_c h^2, \theta, \tau, n_s, A_s$. Here, Ω_b is the baryon content, Ω_c is the cold dark matter content, θ is the acoustic peak angular scale, τ is the optical depth, n_s is the power-law spectral index, and A_s is the normalization.

Adding this perturbation to the primordial power spectrum improves the total χ^2 for the fit from 9803 to 9798. One expects that the effect of interest here would only make a small change ($\Delta\chi^2 = 5$) in the overall fit because it only affects a limited range of l values with large error bars. Nevertheless, from the likelihood contours we can deduce a mean value of $A = 1.7 \pm 1.5$ with a maximum likelihood value of $A = 1.5$, and a mean value of $k_* = 0.0011 \pm 0.0004 \, h \, \text{Mpc}^{-1}$

3. Physical Parameters

The coefficient A can be related¹ directly to the coupling constant λ . This gives

$$A \sim 1.3 N \lambda^{5/2}. \quad (8)$$

Hence, for the maximum likelihood value of $A \sim 1.5$, we have

$$\lambda \approx \frac{(1.0 \pm 0.5)}{N^{2/5}} \quad (9)$$

So, $\lambda \leq 1$ requires $N > 1$ as expected.

The fermion particle mass m can then be deduced from $m = N \lambda \phi_*$. From Eq. (9) then we have $m \approx \phi_*/\lambda^{3/2}$. For this purpose, we adopt a general monomial

potential for which:

$$\phi_* = \sqrt{2\alpha\mathcal{N}}m_{pl} \quad . \quad (10)$$

For $k_* = 0.0011 \pm 0.0004 h \text{ Mpc}^{-1}$, and $k_H = a_0 H_0 = (h/3000) \text{ Mpc}^{-1} \sim 0.0002$, we have $\mathcal{N} - \mathcal{N}_* = \ln(k_H/k_*) < 1$. Typically one expects $\mathcal{N}(k_*) \sim \mathcal{N} \sim 50 - 60$. We note, however, that one can have the number of e-folds as low as $\mathcal{N} \sim 25$ in the case of thermal inflation¹². For standard inflation a monomial potential with $\alpha = 2$ would have $\phi_* \sim (14 - 15) m_{pl}$. However, the limits on the tensor to scalar ratio from the *Planck* analysis⁴ rule out $\alpha = 2$ at the 95% confidence level. Monomial potentials are more consistent with $\alpha = 1$ ($\phi_* = (10 - 11) m_{pl}$), or even $\alpha = 2/3$ ($\phi_* = (8 - 9) m_{pl}$). Hence, we have roughly the constraint,

$$m \sim (8 - 11) \frac{m_{pl}}{\lambda^{3/2}} \quad . \quad (11)$$

So, one can deduce¹ a family of possible properties of the resonantly produced particle (i.e. its mass and coupling strength) in terms of a single parameter, the degeneracy N .

4. Conclusion

We have analyzed the $\ell = 10 - 30$ dip in the *Planck* CMB power spectrum in the context of a model for the creation of N nearly degenerate trans-Planckian massive fermions during inflation. The best fit to the CMB power spectrum implies an optimum feature at $k_* = 0.0011 \pm 0.0004 h \text{ Mpc}^{-1}$ and $A \approx 1.7 \pm 1.5$. For monomial inflation potentials consistent with the *Planck* tensor-to-scalar ratio, this feature would correspond to the resonant creation of nearly degenerate particles with $m \sim 8 - 11 m_{pl}/\lambda^{3/2}$ and a Yukawa coupling constant λ between the fermion species and the inflaton field of $\lambda \approx (1.0 \pm 0.5)N^{-2/5}$ for N degenerate fermion species.

We conclude that if the present analysis is correct, this may be one of the first hints at observational evidence of new particle physics at the Planck scale. Indeed, one expects a plethora of particles at the Planck scale, particularly in the context of string theory. Perhaps, the presently observed CMB power spectrum contains the first suggestion that a subset of such particles may have coupled to the inflaton field leaving a relic signature of their existence in the CMB primordial power spectrum.

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References

1. G. J. Mathews, M. R. Gangopadhyay, K. Ichiki, and T. Kajino, Phys. Rev. **D92** 123519 (2015).
2. *Planck* Collaboration, Astron. & Astrophys. Submitted (2015) ArXive:1502.01589, astro-ph
3. G. Hinshaw, et al. (*WMAP Collaboration*) Astrophys. J. Suppl. Ser., **208**, 19 (2013).
4. *Planck* Collaboration, Astron. & Astrophys. Submitted (2015) ArXive:1502.02114, astro-ph
5. D. J. H. Chung, E. W. Kolb, A. Riotto, and I. I. Tkachev, Phys. Rev. D **62**, 043508 (2000).
6. G. J. Mathews, D. Chung, K. Ichiki, T. Kajino, and M. Orito, Phys. Rev. **D70**, 083505 (2004).
7. L. Kofman, A. D. Linde, and A. A. Starobinsky, Phys. Rev. Lett. **73** 3195 (1994).
8. O. Elgaroy, S. Hannestad, and T. Haugboelle, JCAP, 09, 008 (2003).
9. A. E. Romano and M. Sasaki, Phys. Rev. D **78**, 103522 (2008).
10. N. Barnaby, Z. Huang, L. Kofman, and D. Pogosyan, Phys. Rev. D **80**, 043501 (2009).
11. M. A. Fedderke, E. W. Kolb, M. Wyman, Phys. Rev., D **91**, 063505 (2015).
12. A. R. Liddle and D. H. Lyth, *Cosmological Inflation and Large Scale Structure*, (Cambridge University Press: Cambridge, UK), (1998).
13. E. W. Kolb and M. S. Turner, *The Early Universe*, (Addison-Wesley, Menlo Park, Ca., 1990).
14. N. Christensen and R. Meyer, L. Knox, and B. Luey, Class. and Quant. Grav., **18**, 2677 (2001).
15. A. Lewis and S. Bridle, Phys. Rev. D **66**, 103511 (2002).
16. N. D. Birrell and P. C. W. Davies, *Quantum Fields in Curved Space*, (Cambridge Univ. Press, Cambridge, 1982).